ON INDUCED ELECTRICAL POLARIZATION AND GROUNDWATER†

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Clay horizons and other clay-bearing unconsolidated sediments are potential sources of induced-polarization anomalies. If such anomalies may be detected above system noise, the induced-polarization method may be of value for in-situ classification of unconsolidated sediments encountered in hydrological projects. One such project exists in Santa Clara County where near-surface unconsolidated sediments are frequently considered as potential recharge areas. Of four areas surveyed with induced-polarization apparatus in Santa Clara County, only two yielded significant frequency-effect anomalies, and in each of these two the frequency effects were of the order of 3 percent. These anomalous frequency effects may be related to clayey gravels. The dipole-dipole array, with spreads of 10 ft and 20 ft, was typically used in the study.

INTRODUCTION

The purpose of the study reported here has been to investigate the applicability and limitations of conventional induced electrical polarization equipment in the location and evaluation of natural groundwater reservoirs occurring in unconsolidated sediments in California.

Between 1953 and 1957, Vacquier et al (1957) conducted laboratory and field experiments to determine the applicability of the induced-polarization method to prospecting for groundwater in New Mexico. These initial experiments showed considerable promise, but surprisingly little work was done elsewhere to exploit this pioneering research. Hence Vacquier urged us to expand the base of his original work by studying similar problems in California. Our approach is different than that of Vacquier et al insofar as we have employed frequency-domain induced-polarization (IP) apparatus of a type now standardly available for mineral surveys, whereas Vacquier et al developed equipment specifically designed to obtain parameters of interest in groundwater search.

Basically we have sought to assist in the in-situ classification of unconsolidated clay horizons and gravels with clay. Saline water areas have been avoided, and measurements have been made only at sites where the water occurs within 20 ft of surface.

Sumi (1965) has recorded time-domain induced-polarization survey data over unconsolidated sediments, including horizons containing clay minerals. His research constitutes an interesting reference for the present work. Field studies were carried out in Crimea and Armenia by Kuz'mina and Ogil'vi (1965). They used time-domain IP to study (1) groundwater in areas where high conductivities do not yield good resistivity contrast, (2) paths of groundwater flow in alluvial sediments underlain by extrusives.

Zohdy (1964) made extensive resistivity surveys in the same general area that we have studied. His purpose was the location of permeable strata for groundwater recharge. Our work then constitutes an extension of Zohdy's insofar as we attempt to identify clay-containing gravels. Saline clean gravels may be distinguished from clay-containing fresh water gravels only by induced-polarization *and* resistivity measurements, and not by resistivity alone. In the search for rechargeable strata, this distinction is of importance. Solid clay horizons respond as resistivity lows but do not typically produce induced-polarization highs. Since these horizons serve as impermeable barriers to water percolation, it is important to map them electrically, and resistivity soundings and surveys usually accomplish this.

SOURCES OF INDUCED-POLARIZATION ANOMALIES IN UNCONSOLIDATED SEDIMENTS

Both Vacquier et al (1957) and Sumi (1965) have presented discussions of the sources of induced-polarization anomalies in unconsolidated sediments. The findings from the research of Vacquier et al pertinent to the present discussion are as follows:

1. In water-saturated sandstone or alluvium, induced polarization appears when the surfaces of the sand and gravel are partially coated with a film of clay.
2. Clean quartz sand saturated with water shows almost no effect.
3. The magnitude of the induced polarization depends in a complicated way on the resistivity of the solution, on the amount and kind of clay, and on the particular cation saturating the clay.
4. Generally, the polarizability decreases with decrease in resistivity, so that clay horizons and saline waters give small effects.
5. The dependence of polarization on the amount of clay is complex; for amounts greater than three percent, it depends on whether the clay is flocculated or dispersed.
6. Saturation with sodium or potassium tends to make the clay swell so as to fill up the pores of the matrix, causing a drop of the polarization when too much clay is present. The same clay, when saturated with calcium, is flocculated into aggregates immersed in the electrolyte. These aggregates make a porous mass even without the addition of sand. With flocculated clays, the polarizability increases with increasing clay content up to about 5 to 9 percent of clay by dry weight.
7. The polarizability of the sand-clay mixtures is roughly proportional to the ion-exchange capacity of the clay. Thus montmorillonites are more active than kaolinites.
8. The rate of decay of charge accumulation depends only on the grain size of the aquifer.

The above findings are consistent with the following phenomenological explanation of induced-polarization anomaly sources.

The induced-polarization method of geophysical exploration is based upon the fact that the resistivity of earth materials is occasionally found to be a function of frequency of applied current. This frequency-dependent resistivity is a consequence of the development of a double layer of electrical charge at the surface of some materials. Clay minerals exhibit a pronounced double layer, because, for example, substitutions within the crystal lattice lead to a net unbalance of electrical charge which must be balanced by an adsorbed layer of cations. The thickness of this adsorbed layer is of the order of 100 microns, but varies according to the salinity of the water in contact with the clay mineral; the higher the salinity the thinner the double layer.

When clay minerals are distributed in micropores in rock or soil, the clay double layer, consisting of fixed and diffuse adsorbed cations, may partially or completely block the pore. An ion-selective zone is thereby developed; anions are blocked by the zone, and cations are passed readily (Figure 17, Ward & Fraser, 1967). If the clay particle is physically immobile and an alternating voltage is applied to a volume of rock or soil, an accumulation of charge will occur alternately on either side of the ion-selective, or membrane, zone. There is a lag of development of the zone of charge accumulation relative to the applied voltage. This behavior is loosely analogous to that of a capacitor. Hence we expect that the electrical impedance of a pore containing a membrane zone will be frequency dependent. The process is diffusion controlled since the ions must diffuse through the region of the membrane zone if electrical equilibrium is to be reached upon cessation of application of a voltage. Not all pores in rock or soil are even partially blocked by membrane zones arising in clay minerals. We usually find that sandy sediments or gravels, in which clay minerals form a minor part, often give rise to appreciable induced electrical polarization. Massive clay horizons may or may not produce induced polarization depending upon the clay type and state.

Since kaolinite particles produce diffuse layers only at their surfaces, these clay particles must occur in very narrow rock pore capillaries in order that the membrane be significant. Otherwise the membrane will be bypassed by purely resistive paths. For montmorillonite particles, abnormal water exists between the alumino-silicate layers. Conduction through this abnormal water, which is cation selective, is thus less dependent on the geometry of the pores or capillaries within a soil or rock. This, in conjunction with the large surface activity of montmorillonite, implies that the existence of montmorillonite clay particles in a soil or rock may produce a larger polarization than a like amount of other clay minerals. Vacquier et al (1957) as well as Marshall and Madden (1959) are quite definite in their statements that massive clay horizons produce small polarizability. Arulanandan (1966) presents a fairly complete discussion of polarizability of clay-water

systems. Additional authors who have considered polarization due to clay minerals include Anderson and Keller (1964), Keller and Licastro (1959), Henkel and Van Nostrand (1957), Mayper (1959), and others.

The membrane mode of development of induced electrical polarization is not the only one which exists. On the contrary, metallic minerals disseminated in amounts as small as one percent in a rock frequently produce more polarization than the most polarizable clay-containing rock. The metallic mineral magnetite produces much less polarization than the sulfide minerals and, in fact, seldom is of significance to polarization phenomena in amounts up to one percent. Both sulfide minerals and magnetite may occur in unconsolidated sediments although the former are relatively rare.

Since the presence of clay minerals leads to polarization phenomena and also, for the same electrochemical reasons, leads to a reduction of fluid permeability, there is the possibility of evaluating fluid permeability in situ by means of induced polarization. Vacquier et al (1957) made reference to this possibility in their conclusions and Latishova (1953), Latishova and Dobrineen (1955), and Kumar (1962) have demonstrated the relationship between fluid permeability and induced polarization of petroleum reservoir rock samples in the laboratory.

More complete discussions of induced-polarization (IP) phenomenology are contained in the writings of Marshall and Madden (1959), Wait (1959), Arulanandan (1966), Seigel (1959), and Madden and Cantwell (1967).

DATA MEASUREMENT AND PORTRAYAL

The equipment used during this survey was a McPhar Geophysics Ltd. Model 2006 IP unit, utilizing measurements in the frequency domain. In this IP system, current is applied at selected frequencies via two grounded electrodes; the resulting ground potentials are measured at two other electrodes. If the ratio of measured voltage to applied current is not the same when two different frequencies are used, it is apparent that polarization is occurring and an IP anomaly exists. The magnitude of the difference in response at different frequencies is proportional to the amount and polarizability of polarizable material in the subsurface.

In the frequency-domain technique, the in-

duced-polarization effect is determined by measuring the ground resistance (more correctly the magnitude of the impedance of the ground) at two frequencies. This is done, as stated above, by applying a known current to the ground through two electrodes and measuring the potential drop across two other electrodes, the measurement being carried out at the two frequencies simultaneously.

The equipment was battery operated with a maximum output of 450 volts; the frequencies used in this standard unit are 0.3 and 5 Hz. Theoretically, the IP effect could be detected at any frequency up to several thousand Hertz. However, above some frequency, the inductive coupling between the current and potential leads, as effected by the presence of the earth, produces spurious frequency-dependent voltages in the measuring circuit.

Of the different electrode configurations used in resistivity measurements, Wenner, Schlumberger, pole-dipole, and dipole-dipole are the most common. In this survey the last one has been used primarily in order to minimize coupling between transmitting and receiving circuits. In it, all four electrodes are collinear. The current is applied through a dipole consisting of two electrodes of separation l, and the potential drop is measured between two other electrodes constituting the potential dipole, also spaced a distance l apart. The distance between the nearest current and potential electrodes is xl, where l is a variable integer between 1 and 4. The larger x or l, the greater is the depth of exploration. Because of the shallow features to be studied, the spreads used in this survey were very short ones: 10-ft and 20-ft.

Two parameters were used to describe the results of the IP survey:

Apparent resistivity

The potential we would measure above a homogeneous half-space is given by the following formula:

$$V = \frac{\rho}{2\pi} I \frac{2}{x(x+1)(x+2)} \frac{1}{l} .$$

By analogy, we define the apparent resistivity as ρ_a, pertaining to an inhomogeneous earth, and the formula defining it as:

$$\rho_a/2\pi = \frac{V}{I} \; \frac{x(x+1)(x+2)}{2} \, l.$$

If distances are measured in meters, voltages in volts, currents in amperes, apparent resistivities are expressed in ohm-meters.

Frequency effect

At two different frequencies, different impedances will generally be measured. The normalized difference in impedance will define the "percent frequency effect" (PFE) as

$$\left[\frac{|Z_{\text{low frequency}}|}{|Z_{\text{high frequency}}|} - 1 \right] \times 100\%.$$

This number is in general positive, high-frequency impedances being smaller than low frequency impedances. However, if the current paths are not the same in both cases (due to local inhomogeneities, for instance), then negative numbers may appear.

In the field, the measurements were conducted in the following way. Each potential measurement was preceded and followed by a calibration. The frequency effect reading between calibrations oscillates or drifts as a function of time as a result of instrument instability. The reading was still considered acceptable when the drift between successive calibrations became of the order of 0.4 PFE. An average drift of less than this amount was experienced. Repeat measurements of complete traverses suggested that we could repeat a frequency effect reading to less than ± 0.3 PFE.

Some small part of the drift in the frequency effect could be attributed to disequilibria between the copper potential electrodes and the soil which had been wetted with a saturated NaCl solution. However, the use of Cu-CuSO₄ porous pot, non-polarizing electrodes, instead of copper electrodes, did not yield better results. Low current density, coupled with high ambient electrical noise levels, can also give rise to errors and hence time variations in observed frequency effects. Careful current and potential electrode preparation assuring electrode-to-ground impedances less than 200 ohms can minimize this source of error.

Field results are plotted on plan maps, one for each parameter for each separation x, and contoured, or alternatively they are plotted on vertical quasi-sections according to conventions appearing in the literature (e.g., Hallof, 1966).

LOCATION AND GEOLOGIC SETTING OF SURVEYED AREAS

The map of Figure 1 shows the four sites where induced electrical polarization experiments were carried out. They are all located in the lower part of Santa Clara Valley, around the city of San Jose. This part of the valley is roughly situated between the San Andreas fault and the Hayward fault, or the Santz Cruz Mountains and the Mount Hamilton Range.

Poland and Green (1962) have described the geology of Santa Clara Valley as follows:

"The bedrock, shown as a single unit on the map, ranges in age from Jurassic to Pliocene and consists principally of consolidated sedimentary rocks but includes minor areas of metamorphic and igneous rock. Overlying this consolidated bedrock is the Santa Clara formation of Pliocene and Pleistocene age. Where exposed, the Santa Clara consists of semiconsolidated conglomerate, sandstone, siltstone, and claystone. The conglomerate and sandstone are poorly sorted and have a fine-grained matrix; thus the formation has a low permeability and yields only small to moderate quantities of water to wells, rarely enough for irrigation purposes. Along the western margin of the valley, the Santa Clara was warped and folded during the last uplift of the Santa Cruz Mountains. Beneath the valley the formation may be undisturbed and in part conformable with overlying beds.

"Unconsolidated alluvial and bay deposits of clay, sand, and gravel overlie the Santa Clara formation and form the valley floor. As shown by well logs, the alluvial and bay deposits reach a thickness of 1,000 ft or more in the valley trough. However, the lower parts of these wells may be in the Santa Clara formation, which to date has not been differentiated from the overlying unconsolidated alluvium in drillholes.

"Fine-grained materials such as clay, silt, and sandy clay, which retard the vertical movement of confined groundwater, constitute the major part of the valley fill. Sand and gravel occur in lesser amounts but are more abundant near the valley margins and in old stream channels. None of the deposits can be traced laterally for more than a short distance."

In Santa Clara Valley active work is being done by the Santa Clara Valley Water Conservation
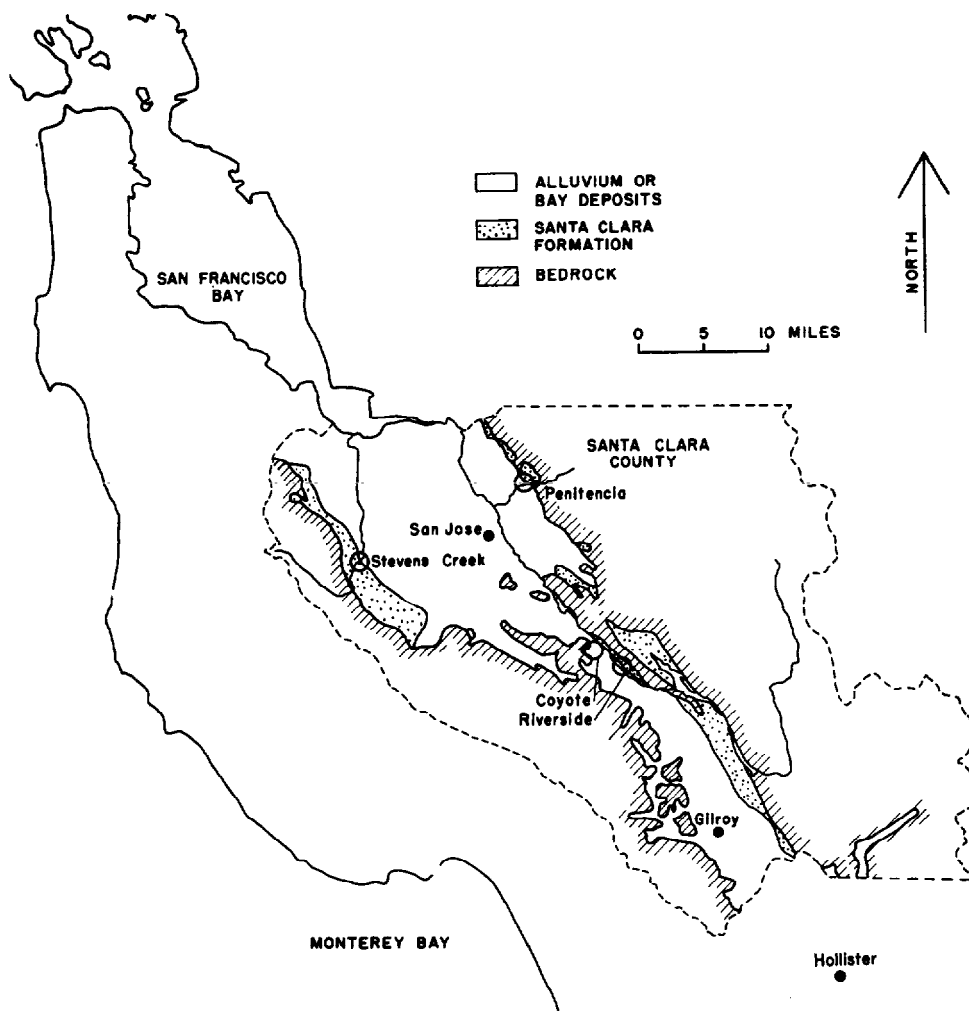
Fig. 1. Locations of the four sites in Santa Clara County, California,
where induced-polarization surveys were conducted.

District directed toward creating potential re-
charge areas. Much information was available
from the District regarding lithology and water
table. In all four sites, test holes had already been
drilled, and in different areas extensive electrical
studies were carried out in the past by Zohdy
(1964).

At two sites, Riverside and Penitencia, Figures
2 and 3, typical IP anomalies were encountered,
and special attention has been given to them. The
results obtained at the two other sites, Coyote and
Stevens Creek, will not be presented here. They
did, however, permit a study of interpretation
methods for resistivity surveys made with dipole-

dipole configurations. A separate document
(Bodmer and Ward, to be published) reports on
resistivity interpretations at one of these sites.

DISCUSSION OF RESULTS, RIVERSIDE

The Riverside area was surveyed early in 1966
by consulting engineers and geologists for the
purpose of constructing an access road to a large
future community and for mapping the potential
near-surface recharge areas to be used for the
community's water supply. The preparation for
this road and a bridge across Coyote Creek has re-
sulted in sampling of the unconsolidated section
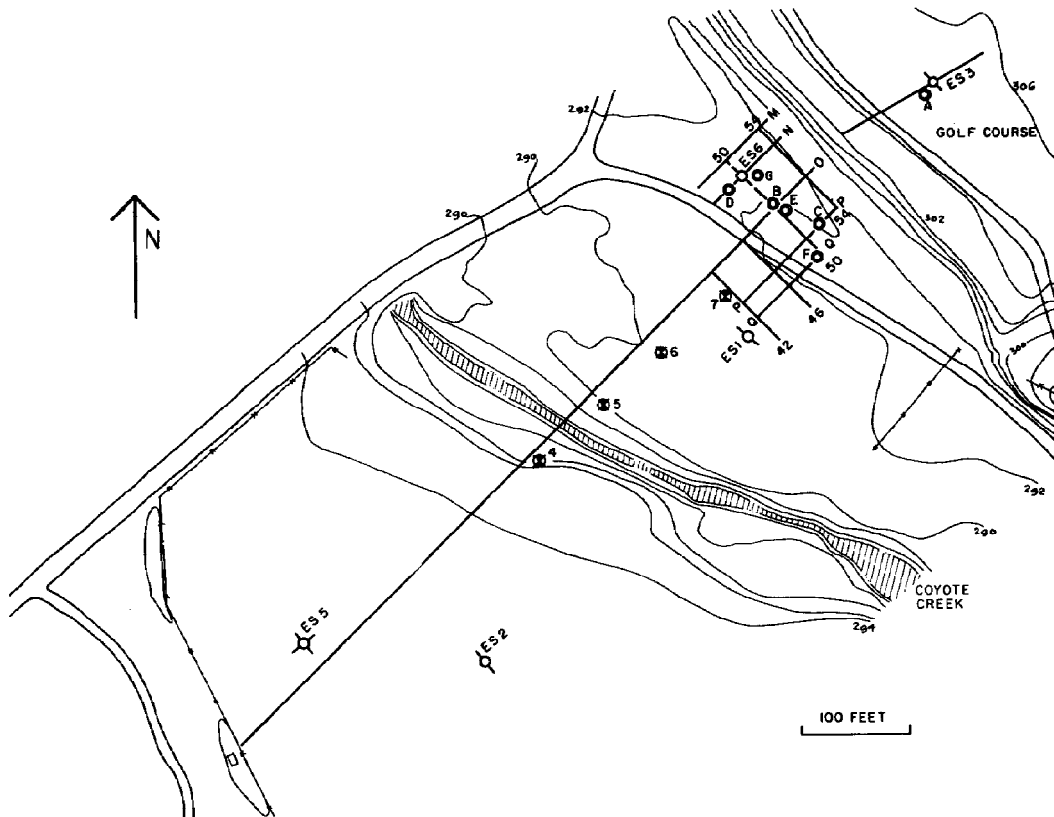by drilling. While this drilling was widely spaced,

FIG. 2. Traverse lines and drill holes at Riverside site.

it did provide the knowledge that clays, clean gravels, and gravels with clay were to be expected. We chose to work where we could expect some sharp contrast in conductivity, such as a relatively clean gravel cover overlying dense clay as exists near Coyote Creek.

At this site the reconnaissance traverse 0 of Figure 2 was surveyed with 10-ft dipoles used in a dipole-dipole array with $x = 1, 2, 3$, and 4, as described above. The northeast end of this profile showed anomalous frequency effects. Hence, additional traverses were made, four parallel and four perpendicular, as shown in Figure 2. Therefore a plan contour map could be prepared for each dipole separation $x = 1, 2, 3$, and 4, presenting resistivity variations on one hand and PFE variations on the other as in Figures 4 and 5. Clear cut anomalies show in the frequency effect for each separation, but they do not in general correlate with the resistivity anomalies. There is a broad resistivity low in crude coincidence with the PFE

high for $x = 1$, but no similar statement can be made for the larger dipole separations. Therefore we conclude that the source of the PFE anomaly is not a source for a resistivity anomaly.

The same area was surveyed with a dipole-dipole array of 20 ft spread length. Readings were only obtained for the first two separations and good agreement with the 10-ft dipole results was observed.

The maximum observed frequency effect of about 3.5 percent occurs near the intersection of the line 0 with line 50 (Figure 5) and was obtained with 10-ft dipoles. The contours show a trend oriented roughly north-south. At both ends the source of anomaly appears to be deeper.

The resistivity quasi-section depicts a typical horizontally layered earth. In Figure 6, which represents a section through the area of maximum frequency effect, no significant lateral variations in resistivity can be observed. A slight dip towards the southeast is the notable feature. Fraser
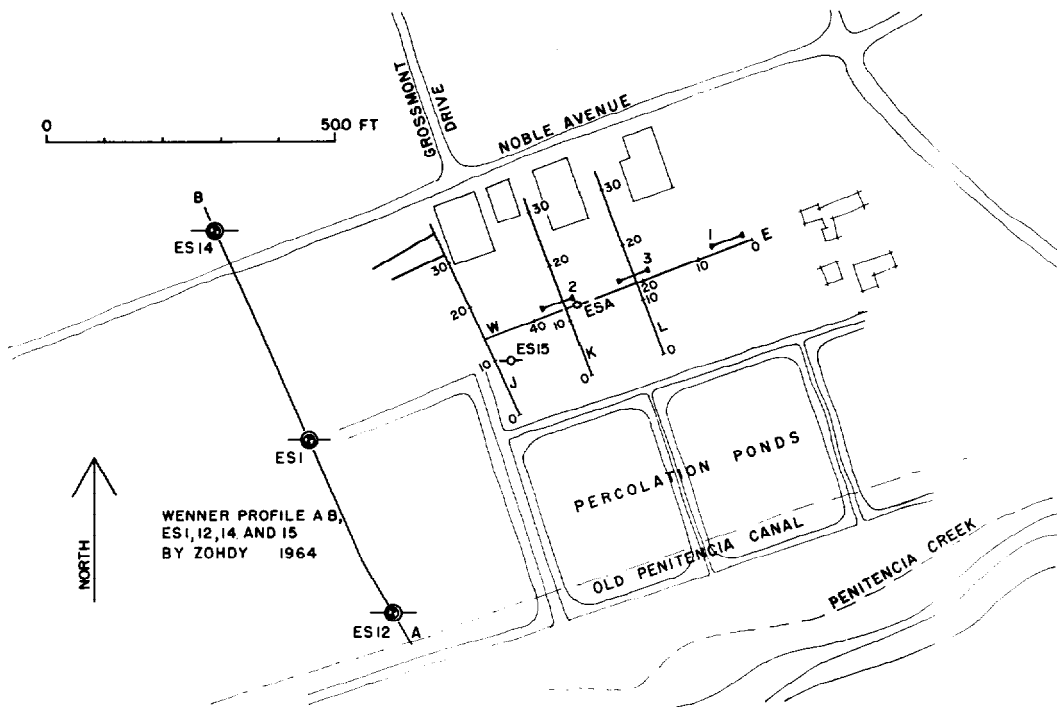
FIG. 3. Traverse lines and electrical soundings ES A, ES 1,
ES 12, ES 14, and ES 15 at Penitencia site.

and Ward (1965) presented a method for simple interpretation of two-layered structures from dipole-dipole data. We have applied this method and obtained:

	Apparent Resistivity		Depth
	1st layer	2nd layer	
North-West end	396 ohm-m	4 ohm-m	9 ft.
South-East end	358 ohm-m	4 ohm-m	11 ft.

Test drilling yielded a depth of 10–12 ft to a blue clay horizon above which were gravels as shown in Figure 7. On the frequency effect section of Figure 6, as much as 3.5 PFE is mapped; the pattern of the contour lines between holes B and C indicates a polarizable body which is vertically and horizontally confined, i.e., lens-like. The contour lines are inclined on both sides at an angle of approximately 45 degrees and show definite flanking highs which bracket a central low. A deeper polarizable inhomogeneity lies midway between holes B and D.

Figure 8 contains a section oriented perpendicular to the previous one. The anomaly near 0–50

is detected, and the same diagnostic pattern occurs.
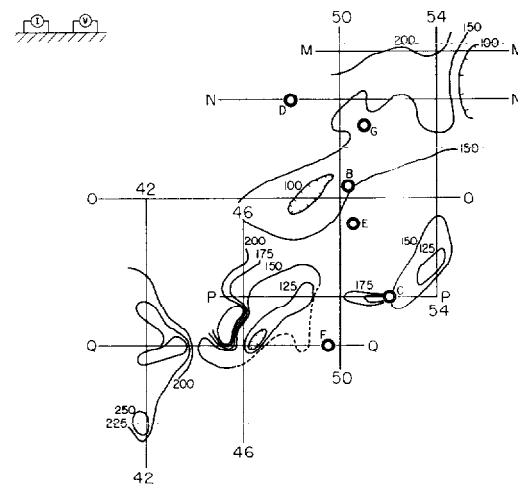
Wenner soundings and seismic refraction sur-

FIG. 4. Contours of apparent resistivity, $\rho_a/2\pi$, in ohm-ft for $l=10$ ft, $x=1$, at Riverside site. Plan.
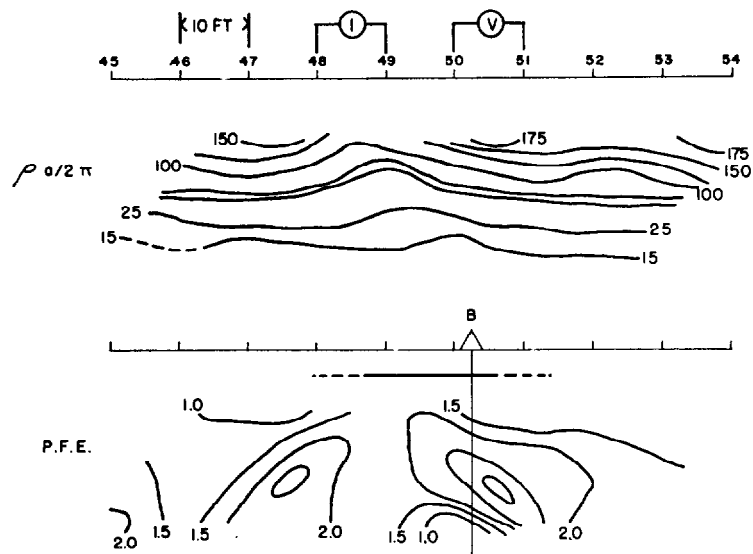
Fig. 5. Contours of percent frequency effect, PFE, for $l = 10$ ft, $x = 1$, at Riverside site. Plan.

Fig. 7. Geologic section, Riverside site, established through drill holes B, C, D, E, G, projected onto a common section.

veys were also performed around this anomaly. The Wenner sounding was in good agreement with the previous interpretation of the dipole-dipole information, yielding interfaces at 9 and 38 ft with layer resistivities of 420 ohm-m, 4.2 ohm-m, and 42 ohm-m. The seismic interpretation was rather qualitative since the area presented lateral inhomogeneities. Away from the anomaly

three layers were recognized with interfaces at 1.3 ft and 9.5 ft and velocities of 1250 ft/sec, 2120 ft/sec, and 4165 ft/sec. Evidently the top of the blue clay is a good marker horizon for both resistivity and seismic refraction methods. Above the anomaly, the traveltime curve takes intricate shapes. Although no interpretation of theoretical character was carried out, these curves at least confirmed the presence of an inhomogeneity. The refraction seismic "fanshooting" technique was then employed and detected a body of higher velocity, as illustrated in Figure 9. This higher

Fig. 6. Apparent resistivity, in ohm-ft and of percent frequency effect PFE for $l = 10$ ft on line 50 at Riverside site. Quasi-section facing northeast.

Fig. 8. Apparent resistivity in ohm-ft and of percent frequency effect PFE for $l = 10$ ft on line 0 at Riverside site. Quasi-section facing northwest.
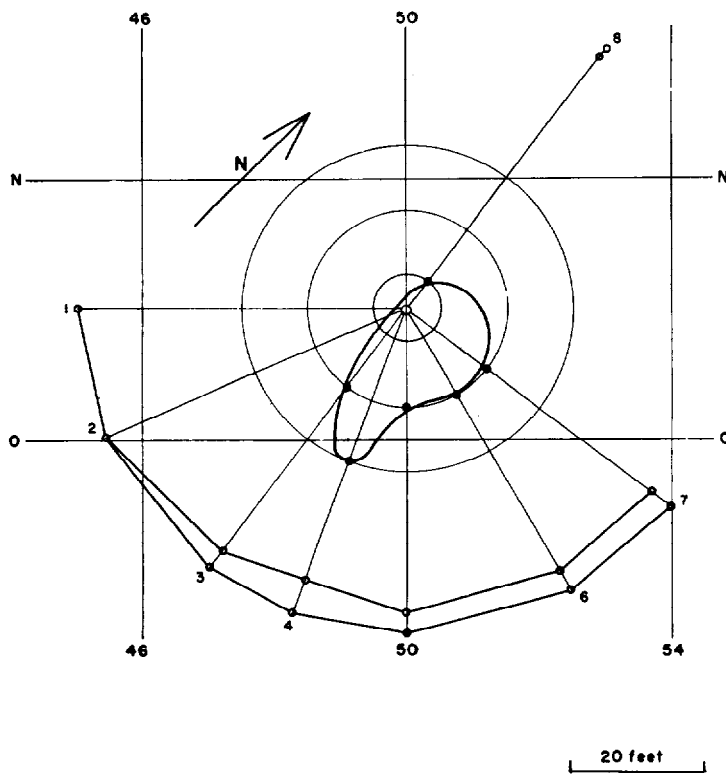

Fig. 9. Results of fanshooting, with hammer seismic apparatus, at Riverside site.

velocity can be indicative of compaction due to clay in sand or gravel, and therefore offers better continuity for propagation.

Several test holes were drilled on this anomaly, the locations of which appear in Figures 4 and 5. Samples were collected with a splitspoon. In holes A, B, C, and D, a 2-inch splitspoon was used every 5 ft; and in the three others, E, F, and G, a 2.5-inch splitspoon sampled every 2.5 ft. From the recovered samples, the geologic cross section of Figure 7 was derived. The expected blue clay formation appears between 10 and 11 ft overlain by gravels partly saturated with water. The holes through the anomalous areas (B, E, G) show a higher visual content of clay than the others in which the samples appeared to be more sandy.

A careful analysis of 14 samples from the holes was carried out, involving the following operations:

—Wet grinding
—Oven drying (140° F)
—Dry grinding
—Sieve analysis
—Hydrometer analysis with finest particles (<0.074 mm) (continuous sedimentation process)
—Specific gravity test
—X-ray spectroscopy (of finest particles).

The mechanical analysis yielded results showing twice as much clay in samples of hole B than in those of holes C and D. In the gravels of hole E only 20 to 30 percent more clay than in those of holes C and D was encountered. A negligible clay content was found in hole G.

A heavy mineral separation was performed on some samples in the particle size range of .07 inch to .151 inch and .151 inch to .33 inch. Less than 0.1 percent of heavy minerals could be detected (some negligible amounts of magnetite being included in this fraction). From the x-ray analyses we observed that all samples bore α-quartz, kaolinite, dickite, chlorite, montmorillonite, and nontronite. Sharper peaks have shown up for the clay fraction in those samples coming from anomalous areas. In some samples away from the anomaly and especially in all the ones from the dense clay formation, all the quartz peaks were weaker, and no biotite or muscovite could be detected, while it was present in all other samples.

It would appear that the IP anomaly is due to minor concentrations of clay minerals in the matrix of clayey gravels, but biotite and quartz may also be contributing to the anomaly. However, the drilling has not produced as much conclusive evidence as one might wish. Another factor which can be expected to be important is the texture; this, however, could not be studied from the samples recovered and would present many practical problems to investigate.

DISCUSSION OF RESULTS, PENITENCIA

This area is characterized by clay members within sand and gravel, crossed by a buried stream channel. Therefore lateral inhomogeneities were expected, so that electrical soundings might not be a very accurate method of investigation. Profiling, however, would tell much more about the presence and location of such structures. Zohdy (1964) covered approximately 28.5 acres
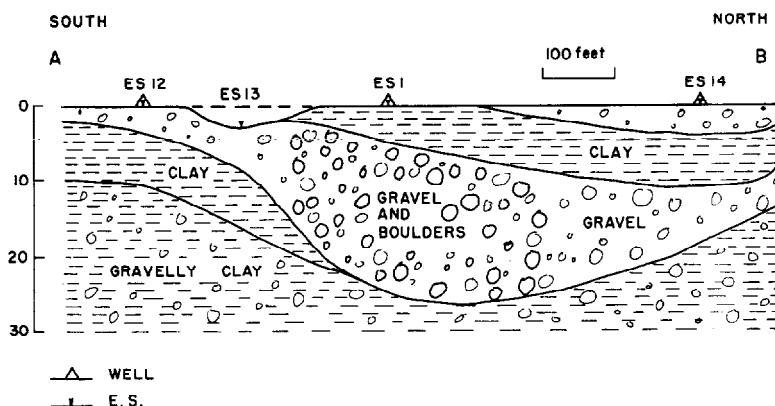

Fig. 10. Geologic section at Penitencia site (after Zohdy, 1964).

profiling with a Wenner arrangement of 20 ft spread length at this site. In Figure 10 Zohdy's interpretation of such a profile is reproduced. This interpretation was based on electrical soundings ES 1, ES 12, ES 13, and ES 14, and on three test holes. This area is now partly occupied by several percolation ponds, fed by pipelines coming from the San Joaquin Delta, and now affecting the groundwater distribution. According to information from the Santa Clara Valley Water Conservation District, the level of the water table rose at one well near the percolation ponds from about 240 ft before their establishment up to 120 ft two years later. Other wells in this area showed similar behavior. Water is flowing out of the surface percolation ponds laterally through more permeable zones coinciding probably with buried stream beds at depths between 10 and 50 ft. These stream beds occur on top of an impermeable formation which is considered as corresponding to older alluvium. In this latter formation, downward percolation can occur, but at a very slow rate.

Since much information was available from Zohdy's work, only one electrical sounding was made, and this is labelled ES A in Figure 3. Much of the area covered by Zohdy in 1963 is now occupied by the ponds, so that the area available to us for survey lies on its edges. The Wenner curve we obtained for ES A showed a four-layered structure. Zohdy's closest sounding at ES 15 revealed a three-layered structure. A comparison of the interpretations of the soundings at ES A and at ES 15 is as follows:

ES A			ES 15		
h_1	3	ρ_1 150	h_1	4	ρ_1 60
h_2	4	ρ_2 50	h_2	13	ρ_2 240
h_3	10	ρ_3 450	h_3	—	ρ_3 60
h_4	—	ρ_4 60			

h in ft, ρ in ohm-m.

At a depth of 17 ft, the two soundings are in agreement. The discrepancy above that horizon may arise from lateral inhomogeneities and possibly also from interpretation inaccuracy. However, a relatively thick resistive layer (10 to 13 ft) shows up in both cases and their resistivities are of the same order of magnitude.

Two perpendicular lines were traversed, in an initial IP survey, with three different dipole lengths: $l=10$ ft, $l=20$ ft, and $l=40$ ft. The first of these, line WE, in Figure 3, was oriented east-west, parallel to the Wenner sounding. Near the middle of this traverse a distinctive shallow PFE anomaly was encountered for $l=10$ ft, as Figure 11 indicates; in general the frequency effects increase with depth suggesting a polarizable layer under a nonpolarizable layer. On the other hand the pattern of the contour lines does not suggest a simple layered structure for $l=20$ ft (Figure 12). For $l=40$ ft (Figure 13), there is a strong suggestion that a nonpolarizable layer underlies the polarizable one, for the PFE values decrease with depth. Both the 20 and 40 ft dipole quasi-sections show upwarpings of contours near stations 20 and 30, confirming the $l=10$ ft data in these regions.

The discrepancies between $l=10$, 20, and 40 ft data may be accounted for by a thin lens of polarizable material lying above a thin bed of polarizable material. The $l=20$ ft survey evidently does not define the lens nor denote the bottom of the thin bed. Resistivities decrease continuously with depth until a more resistive horizon is detected at $l=40$ ft, $x=4$. (Compare Figures 11, 12, and 13.)

Line L, Figure 3, was then traversed, and the IP anomaly detected by 10-ft dipoles on line WE was confirmed. Its location is between stations 13 and 17 as depicted in Figure 14.

The above results suggested that a shallow polarizable thin lens of elongate shape and oriented east-west might be present close to the intersection of the lines WE and L. On line WE we were traversing a short distance along it, while on the second we were crossing it. To confirm this interpretation, lines J and K were surveyed using only the 20-ft array. The PFE anomalies obtained on lines J and K are very small and shallow.

In Figure 15 we have contoured the apparent resistivity values obtained from all traverses with $l=20$ ft and $x=1$. The outline of the IP anomaly has been indicated on this map also. The IP anomaly has the same trend as the resistivity contours but occurs on the north flank of a resistivity high passing through the junction of lines WE and J. According to Zohdy (1964) this latter resistivity high is due to gravels of a buried stream channel. The polarizable body, represented by the IP anomaly, then is on the north edge of the stream
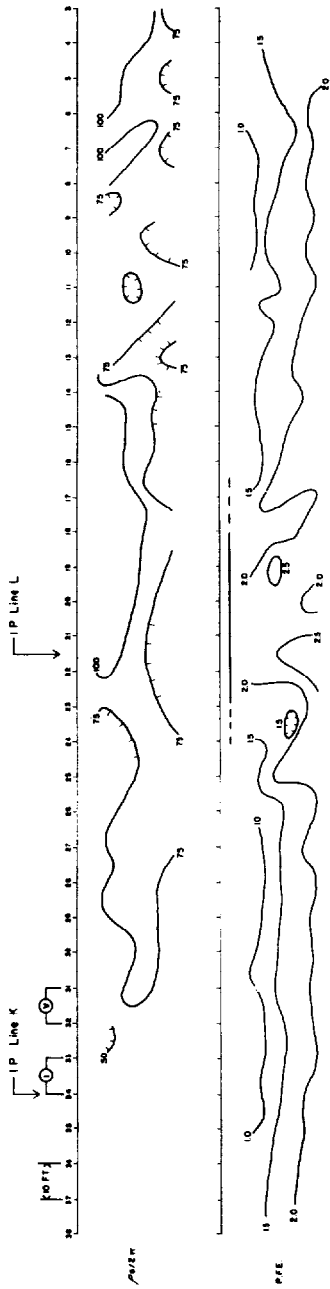
FIG. 11. Apparent resistivity in ohm-ft and percent frequency effect PFE for $l = 10$ ft on line WE at Penitencia site. Quasi-section facing north.
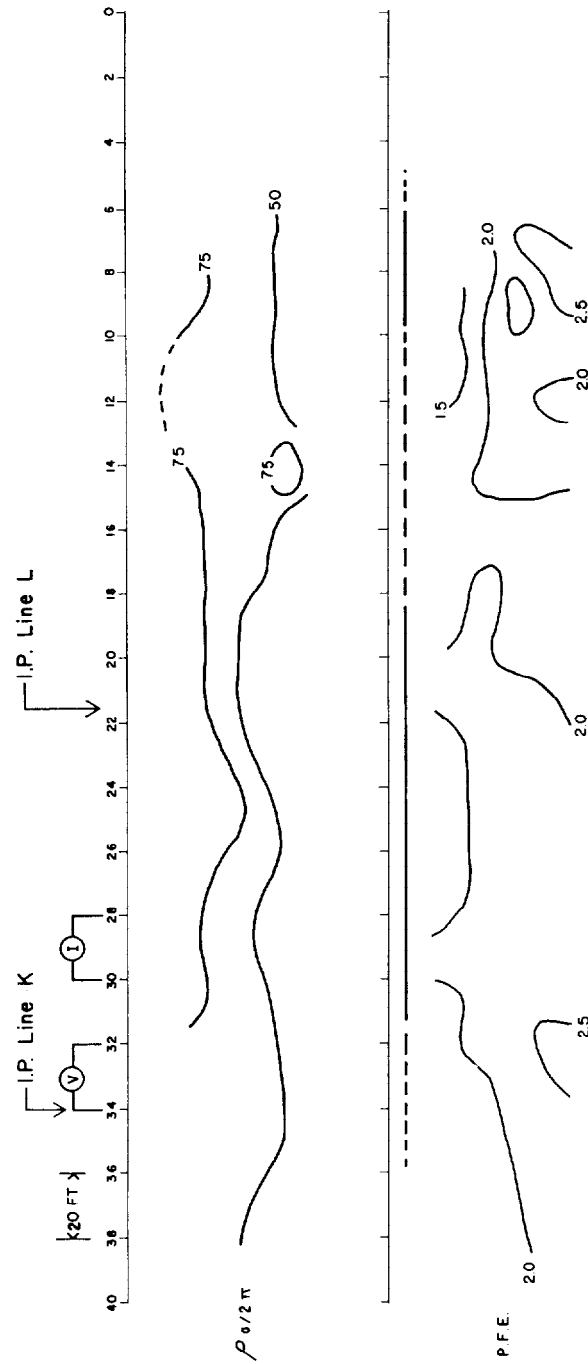
FIG. 12. Apparent resistivity in ohm-ft and percent frequency effect PFE for $l = 20$ ft on line WE at Penitencia site. Quasi-section facing north.
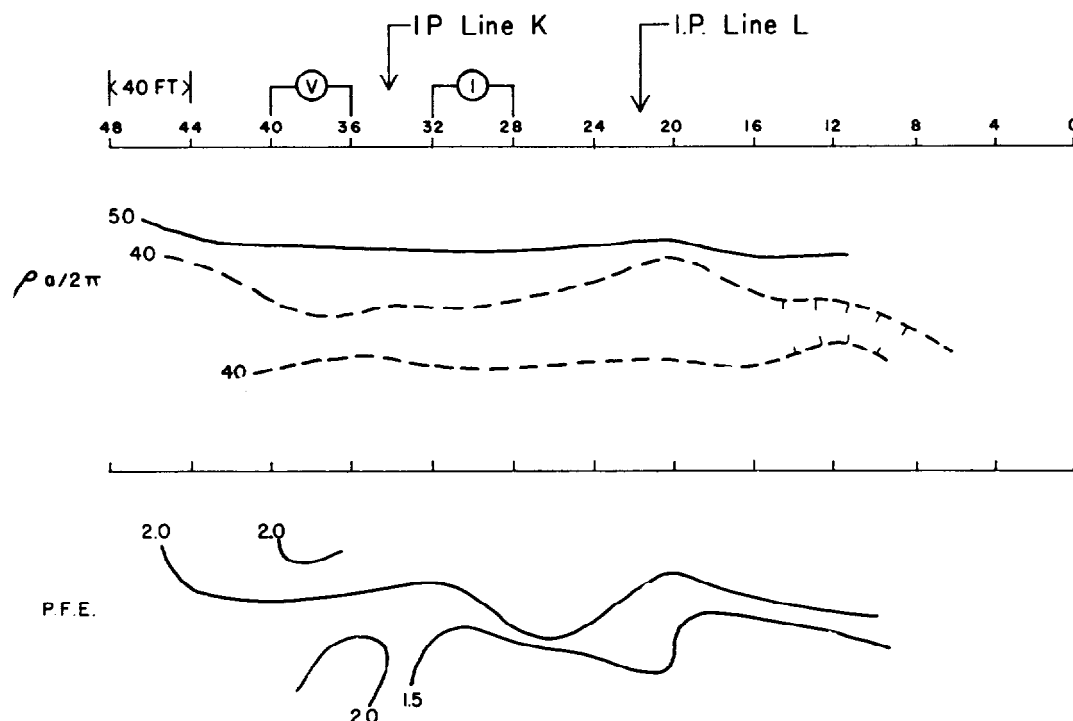
FIG. 13. Apparent resistivity in ohm-ft and percent frequency effect PFE for $l=40$ ft on line WE at Penitencia site. Quasi-section facing north.

channel and would logically be attributed to clayey gravels obtained by the action of the stream on a gravelly-clay through which it was cutting.

Early during the work in Penitencia, three seismic refraction profiles were made along the main line WE; each profile was reversed. Only a simple interpretation has been carried out as if these profiles were independent, and this interpretation is presented in Figure 16.

At the east end, seismic profile no. 1 of Figure 3, it can be considered that the earth is undisturbed and that the traveltime curve obtained represents an average picture of the situation; low velocity material down to 7 ft and more compacted, higher velocity material below. At the west end, seismic profile no. 2, only low velocities have been recorded, probably indicating unconsolidated gravels; this is precisely where higher resistivities occur, according to Figure 15. Seismic profile no. 3 is over the IP anomaly. It seems that higher velocity material has accumulated at the edge of the

buried stream channel. The same type of situation occurred in Riverside where the IP anomaly could be correlated with higher velocities or more compact material.

It has been assumed so far that the only cause of polarizability at Penitencia is clayey gravel. However, to eliminate magnetite as a cause, a magnetic survey was conducted. For this purpose, two cesium vapor magnetometers were used in difference mode. One sensor was fixed outside the area of interest while the other was carried on the grid on which the survey was desired. In general the readings were accurate to 0.1 gamma. Readings were taken on a 5-ft by 10-ft grid of lines spanning the shallow IP anomaly on lines WE, K, and L. The resulting data has been contoured every five gammas and appears in Figure 17. Some local highs and lows show up which arise from shallow features, but none of the anomalies nor any group of anomalies suggest any relation to the IP anomaly, and it is safe to conclude that the polarizable bodies encountered owe this pro-
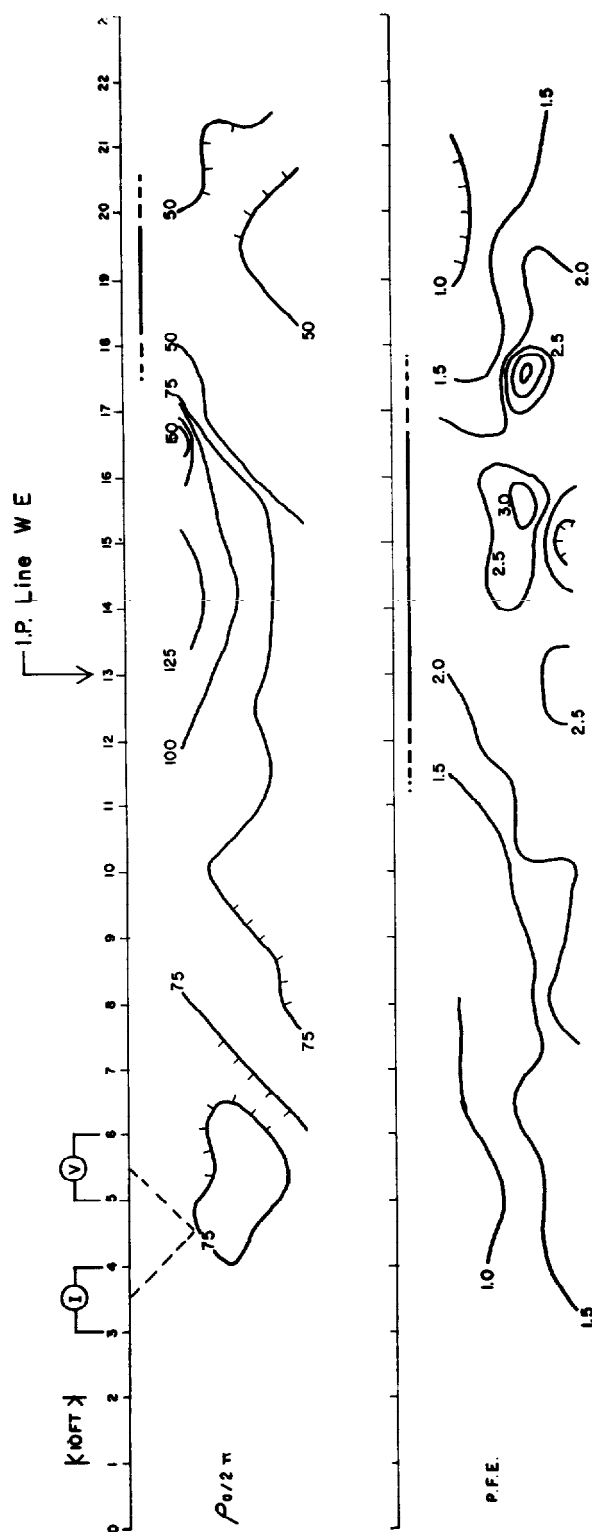
Fig. 14. Apparent resistivity in ohm-ft and percent frequency effect PFE for $l = 10$ ft on line L at Penitencia site. Quasi-section facing west.
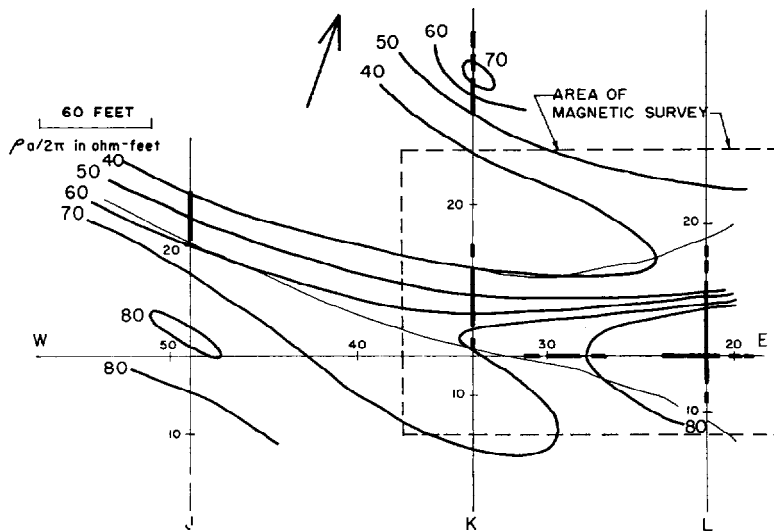
Fig. 15. Apparent resistivity in ohm-ft and outline of PFE anomaly
for $l = 20$ ft, $x = 1$, at Penitencia site. Plan.

perty to clay minerals rather than to magnetite. The small magnetic closures may be attributed to minor metallic debris scattered on the surface.

CONCLUSION

Induced-polarization surveys, in which resistivity is also measured, allow better qualitative interpretation than resistivity surveying alone. In those instances in which the resistivity contrasts are too small to permit delineation of layered materials or lateral variation, PFE anomalies may provide the only means of geologic mapping.

At our Riverside site, the percent frequency effect (PFE) outlined a clay-contaminated gravel which was not evident in the resistivity data.

At our Penitencia site where lateral resistivity changes can be significant, induced polarization mapped a clayey-gravel at the edge of a buried stream channel. Resistivity alone did not draw attention to this clay-contaminated gravel.
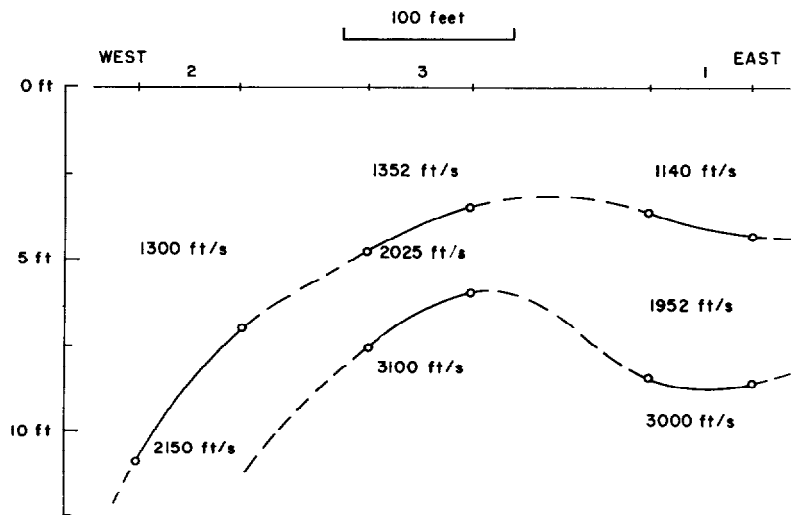

Fig. 16. Interpretation for three hammer seismic refraction soundings on line WE at Penitencia site.
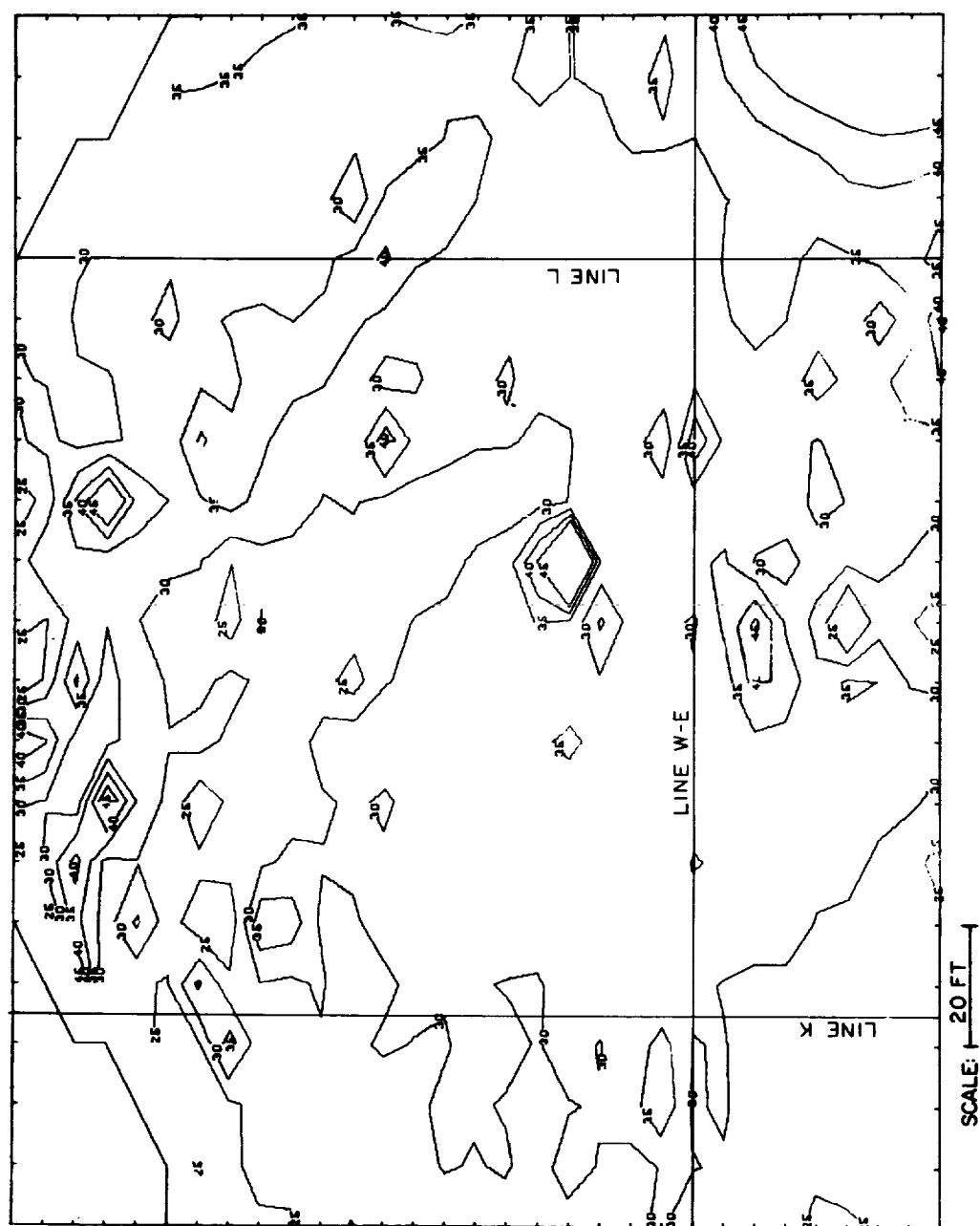
FIG. 17. Computer-contoured total intensity map of central part of Penitencia site. Divisions on horizontal scale are at 10 ft intervals while those on vertical scale are at 5 ft intervals. Readings were taken at the intersections of these grids. Contours in gammas.

SCALE: ⊢ 20 FT ⊣

Permeability is reduced, wherever clays contaminate gravel, so that in some hydrological problems it will be desirable to employ induced polarization to map such zones of low permeability. Membrane polarization is only encountered when a little clay is mixed with sand or gravel. The absence of an IP anomaly will therefore mean either clean gravel, dense clay, sandy clay, or perhaps gravelly clay.

According to Kuz'mina and Ogil'vi (1965), maximum polarization effect has been observed for clay concentrations ranging from 3 to 20 percent. Since this effect depends also on many other parameters like moisture content, particle size, type of clay, and especially texture, the presence of a polarization effect will indicate clayey-gravel but the absence of polarization effect does not demand the absence of clayey-gravel.

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